THE NUMI PROTON BEAM AT FERMILAB SUCCESSES AND CHALLENGES

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Abstract

The NuMI beam at Fermilab has delivered over 5 x10^{20} 120 GeV protons to the neutrino production target since the start for MINOS [1] neutrino oscillation experiment operation in 2005. We report on proton beam commissioning and operation status, including successes and challenges with this beam.

8 GEV BOOSTER AND 120 GEV MAIN INJECTOR

Normal beam operation for NuMI is a mixed mode dual extraction (Pbar targeting plus NuMI) on each 120 GeV Main Injector (MI) beam cycle. Since January 2008, normal operation has been with multi-batch slip stacking of 8 GeV Booster batches in the MI. 2 batches for Pbar production are merged into 1 batch, and 9 batches for NuMI are merged into 5 batches prior to acceleration to 120 GeV [2}. When there is no Pbar targeting, all of MI extracted beam can be sent to NuMI in a NuMI only mode. Test beam operation typically utilizes up to 5% of the beam cycle time.

NUMI PROTON BEAM CONSIDERATIONS

NuMI Beam Parameters

The NuMI proton beam is extracted from the Main Injector with a fast single turn kicker extraction, and a pulse length of 9.6 µsec (for 6 batch extraction). Current operating cycle time is 2.2 seconds. Typical current NuMI beam intensity is 3.0 (mixed mode) to 3.7 (NuMI only) x10^{13} protons per pulse. Operating beam power is ~ 265 kWatts (kW) in mixed mode up to 320 kW in NuMI only mode. Design beam power is 400 kW. After extraction, the proton transport line is bent downward at 156 mradians to a Pretarget beam enclosure and Target Hall, both mined in dolemitic rock. Beam size at the target is 1.1mm σ in both planes. Final targeted proton beam angle is downward by 58 mradians providing aim of the neutrino beam toward the MINOS far detector site located 735 km away in Soudan, MN.

A New Regime for Beam Control Requirements

The most compelling feature for high energy several hundred KW proton beams is that they can damage most materials very quickly. A few seconds or even one cycle of mis-steered beam can readily disable most components, including beam transport magnets and more seriously focusing horns. The latter could lead to very extended downtime. The graphite target is 6.4 mm wide. A pre-target graphite baffle of 11mm ID protects downstream components against most offset parallel beam trajectories. But this protection capability can be compromised when significant beam steering angle is present. The baffle is sized to prevent physics backgrounds from baffle scattering during normal operation.

Other NuMI Beam Constraints

Severe limits on proton beam transport loss are imposed to provide environmental ground water protection as the unshielded beam tunnel passes through an underlying aquifer region. These fractional beam loss limits of a few x 10^{-5} of the beam are also well matched to levels which provide minimal component residual radioactivity.

KEYS TO NUMI PROTON BEAM OPERATION

Several design features of the NuMI proton beam are keys for operation with very low beam loss, as well as prevention of accidental beam mis-steering.

- Comprehensive beam permit system with over 250 parameters verified prior to each beam extraction.
- Open extraction channel and primary transport apertures capable of accepting a range of extracted beam conditions.
- Good beam transport stability, with major power supply regulation to < 50 parts per million, and care with beam optics design.
- Fully automated NuMI beam position control (Autotune),, with no manual adjustment of beam positions required during operation.

Primary extraction channel and transport component apertures were sized to be larger than the Main Injector dynamic aperture of 500 π mm-mrad Typical transverse emittance seen is of order 20 π.

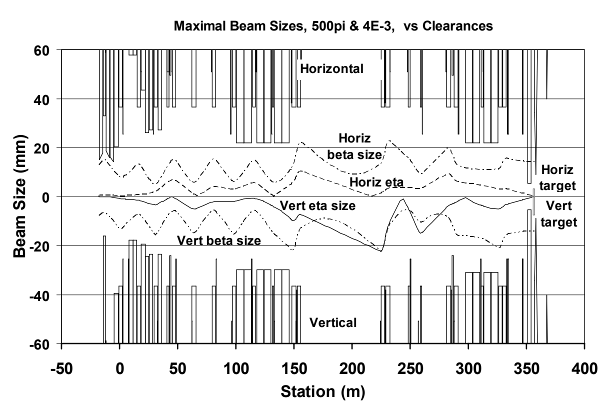

Figure 1: Dispersive (eta) and transverse emittance (beta) maximum beam sizes, vs. component apertures.

Shown in Figure 1 are component apertures compared to the 500 π envelope, plus a conservative momentum spread. Proton beam diagnostics and control are discussed more in another contribution to these proceedings {3}.

COMMISSIONING PLAN AND RESULTS

The NuMI project plan was for the start of beam commissioning as soon as feasible after the accelerator start-up from the Fall 2004 shutdown period. More than one half of the NuMI primary transport is in the Main Injector/Recycler Ring interlock region, with very limited access option. Hence, it was very important to understand NuMI beam issues requiring tunnel access prior to the resumption of MI operation for Pbar production. At this time, significant NuMI target hall installation and checkout time was still needed. To efficiently accomplish both goals, we proceeded with a staged plan for three carefully controlled beam commissioning periods during December 2004 to February 2005.

- December 3-4. First commissioning of the proton beam with target out. We were limited to 150 very low intensity beam pulses of < $3x10^{11}$ ppp as work was still needed inside the target hall beam chase.

Beam was extracted and centered on the hadron absorber 1 km away in 10 beam pulses. Low loss beam transport was established, along with instrumentation checkout. The Beam Permit System was used to enable all beam extractions. Autotune beam control was used at initial corrector turn-on. A total of 44 beam pulses were sent to NuMI during these two days.

- January 21-23. First commissioning of the neutrino beam. Beam intensity was 2.6 x 10^{12} ppp.

With target in place and focusing horns on, neutrino beam was established and first neutrino events seen in the MINOS near detector.

- February 18-22. First high intensity NuMI beam in multi-batch mode, with beam intensity of $2.5x10^{13}$ ppp.

At this stage, the beam commissioning was significantly completed, with capability established for the start of MINOS operation after completion of target hall ventilation and forced air chase cooling systems.

All goals were consistently met or exceeded at each stage of the NuMI beam commissioning process. Prior to initiation of first beam efforts, we had done very comprehensive dry run pre-beam commissioning including:

- Magnet function, polarity checks
- Power supply control, scalings, ramp parameters
- Recycler ring permanent magnet shielding
- Instrumentation function, calibration, readouts
- Beam Permit System, input limits
- Control timing, control programs checks
- Verification of beam documentation capabilities
- Main Injector beam suitable for extraction

The approach taken was that pre-commissioning needed to sort out all problems in advance of first beam. With very few exceptions this was then the result.

Another key to a very efficient beam commissioning was the real time participation of all system experts. We scheduled 12 hour shifts on successive days, instead of 24 hour around the clock efforts. This enabled very efficient resolution of the few problems seen, and. encouraged strong group camaraderie for the beam turn on process.

OPERATIONS EXPERIENCE TO DATE

A number of NuMI target hall system interventions have been required to repair or, on two occasions, replace components. These are challenging one of a kind designs subjected to an intense radiation and corrosive environment. Problems with cooling water systems have been the most numerous, with a more robust design change now in place for horn water line electrical isolators. With sums of greater than 5 $x10^{20}$ protons on target and 24 million beam pulses, we have had one target and one focusing horn replacement.

Shown in Figure 2 are the weekly NuMI protons on target totals in units of 10^{18} protons since the beginning of physics operation in May 2005 for the MINOS experiment. Some features of the plot are a steady climb in integrated weekly totals through the first several months of operation. This then plateaus until the latter part of 2007, with two extended accelerator maintenance and development periods included. An increase in weekly protons on target is again seen in 2008, which is due to the introduction of Main Injector multi-batch slip stacking [2]. Also seen throughout the plot are beam interruptions from one to several weeks duration. Most of these are due to NuMI target hall system interventions, with the most recent one due to the first focusing horn replacement.

Operation of the NuMI proton beam has been very smooth throughout this period. System uptime availability has been 98-99% during each of the first three years, with the most significant interruptions due to change-out of two magnets, after development of cooling water leaks.

Although the NuMI proton beam has much higher beam power than for any previous Fermilab external proton beams, it has also proven to be one of the very simplest to operate. The keys to NuMI proton beam operation as listed previously have led to a very robust system.

We have adapted some systems as needed for improved operation. The most significant of these has been the inclusion of separate corrector file Autotune beam control applications for mixed mode (with Pbar targeting) and NuMI only operation. This is due to small extracted beam momentum differences between the two modes. Switching between modes is a seamless process, with the correct application taking control as needed.

Since commissioning, we have not had the need for dedicated NuMI extraction or proton beam studies, keeping focus toward physics operation.

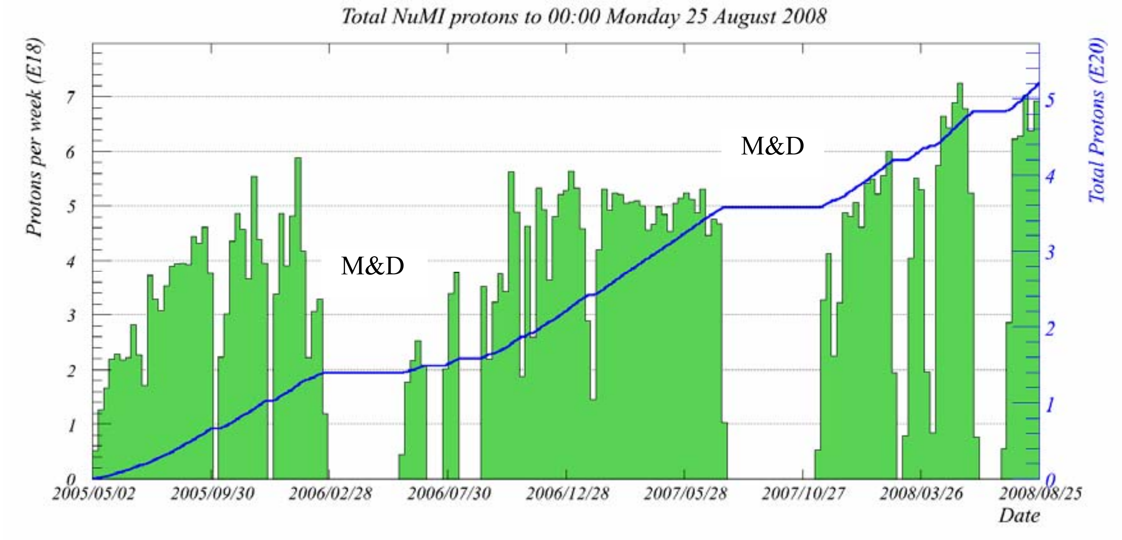

Figure 2. Weekly NuMI proton totals in units of 10^{18} protons since the beginning of operation for MINOS in May 2005. Two extended accelerator maintenance and development periods (M&D) are noted in the figure.

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Over a two year period we have averaged 10 NuMI beam permit system trips per 24 hour day, with monthly averages ranging from 3 trips per day to as high as 21. The great majority of these are reset in 30-45 seconds. Typically. 1 or 2 trips per day require a few minutes to clear, and trips associated with a NuMI component problem needing intervention have averaged about one per week. All major dipole and quadrupole power supplies are ramped and checked at flat top prior to each beam extraction. This involves millions of such checks during each week of operation.

The NuMI permit system has been very effective in preventing proton beam loss. Of 24 million beam pulses to date, we have had a total of five pulses where significant beam loss at the few percent level or greater has occurred. Four of these occurred during the first months of operation.

The combination of the permit system and Autotune beam position control have also been very effective in enabling beam restart after down times for maintenance. Typically, after power supply capability is re-enabled and beam permit system status confirmed, Operations crew chiefs will load in the desired operating timeline, enable the NuMI beam switch and we resume normal operation. No manual NuMI beam system tuning is needed.

Single point beam losses during operation, including through the NuMI beam extraction channel are normally maintained at fractional levels of less than part per million [3]. This provides the very low beam loss environment needed for robust environmental protection, and insures negligible residual activation for proton beam-line components.

ACKNOWLEDGMENTS

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